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Simulation of Recovery Losses Due to Positional Errors in Wellbore Placement

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Summary

In unconventional resources, horizontal wells are drilled in parallel at a spacing distance designed to maximize drainage of the reservoir. Lateral well spacing should be such that the drainage radiuses meet, but do not overlap. If drainage envelopes do not meet, then oil and gas are left stranded in the reservoir. However, due to the limited accuracy of downhole surveying methods, positional errors in wellbore placement often lead to deviations by hundreds of feet from the optimal wellbore position. The purpose of this study is to quantify the impact of such wellbore placement errors on reservoir recovery for different surveying methods.

A recovery simulator web application was developed to approximate the effect of wellbore positional error on reservoir drainage. The application requires input parameters to define the drilling scenario being evaluated. These include lateral wellbore length, lateral well spacing and recovery percentage as a function of the drainage radius. A user selects surveying methods to be compared in the simulation. Using the latest error models of the Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA), the application simulates a large number of wellbores drilled with random errors corresponding to the selected surveying methods. The simulation assesses the expected amount of oil or gas left in the field due to inaccurate wellbore placement. It also provides statistics on the likelihood of wellbore cross-overs and lease line infractions.

Initial results indicate that random errors in wellbore placement lead to hundreds of thousands of dollars in unclaimed hydrocarbons for a typical multi-well pad when using standard Measurement While Drilling (MWD). However, this loss is reduced significantly when applying advanced surveying methods with higher accuracy, such as In-Field Referencing (IFR) and Multi-Station Analysis (MSA). The likelihood of wellbore crossovers and lease line infractions is then also reduced significantly.

Wellbore placement inaccuracy in unconventional plays has not been a major concern until in recent years, when drillers began placing horizontal wells closely spaced together. Modeling positional uncertainty and improving survey accuracy has been driven mostly by drilling professionals in order to mitigate anti-collision risk and keep wellbores within lease lines. However, this study shows that improved wellbore placement has further significant economic benefits by increasing reservoir drainage and providing more accurate data for spacing tests and reservoir models.

Introduction

Oil and gas wells are often drilled horizontally through non-permeable shale formations. In order to extract the hydrocarbons from these formations, the shale rock is hydraulically fractured to enable fluid flow. The resulting fractures extend radially from the wellbore for a limited distance, which creates a production envelope around the wellbore. Since this envelope covers a finite volume, it is necessary to drill multiple horizontal wells within a reservoir in order to recover the full potential of the available hydrocarbons. The spacing between the drilled wellbores is usually determined by the estimated fracture propagation distance that extends outward from the wellbore. Ideally, wellbores should be placed so that the entire space between wellbores is fractured without any overlap. However, there is significant uncertainty in wellbore position when determined from traditional directional surveying technologies. This makes it quite challenging to place wellbores at precise spacing intervals unless operators use enhanced survey management solutions that reduce the positional uncertainty of the wellbore.

Measurement While Drilling (MWD) and Gyro tools are the most commonly used directional surveying instruments for determining wellbore position. However, these tools have numerous error sources that can cause significant inaccuracies in the survey measurements. As a result, wellbore trajectories computed from directional surveys are characterized by ellipses of uncertainty (Figure 1). The size of these EOUs are quantified by the Operator Wellbore Survey Group (OWSG) Instrument Performance Models (IPM), or tool codes (Grindrod *et al.*, 2015).

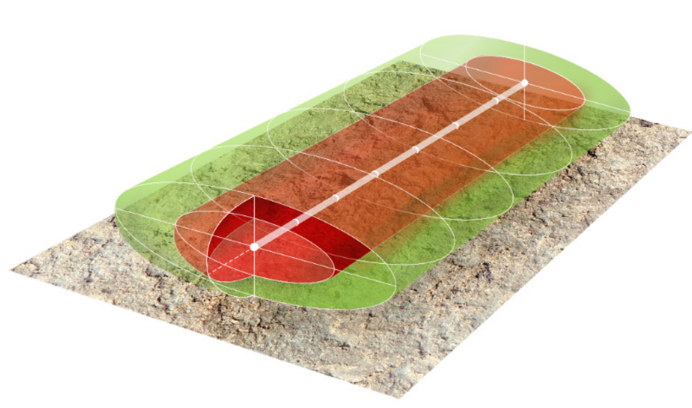

Figure 1: Ellipses of Uncertainty for MWD tool code (green) and MWD+IFR2+MS+SAG tool code (red).

Operators can decrease the size of the ellipses of uncertainty by implementing enhanced surveying techniques such as In-Field Referencing (IFR) and multi-station analysis (MSA). This reduces the survey errors, thus improving the accuracy of the wellbore placement (Maus and DeVerse, 2015). This is advantageous to oil & gas companies because more accurate wellbore placement improves wellbore value.

Wells are planned at spacing designed for optimal drainage, based on fracture propagation, rock characteristics, and formation-specific fluid properties. Wells that are too close can have hydraulic communication between adjacent wells and adversely affect well completions. Wells that are spaced too far apart, on the other hand, do not fully drain the reservoir. Survey error is generally not considered when evaluating well production. Figure 2 shows an example of how wells that were planned to be parallel may actually end up meandering off plan, due to standard surveying errors. Unclaimed resources are left in the reservoir where wells diverge. Neighboring wells compete for the same production envelope where they converge. This study intends to simulate these effects on field production.

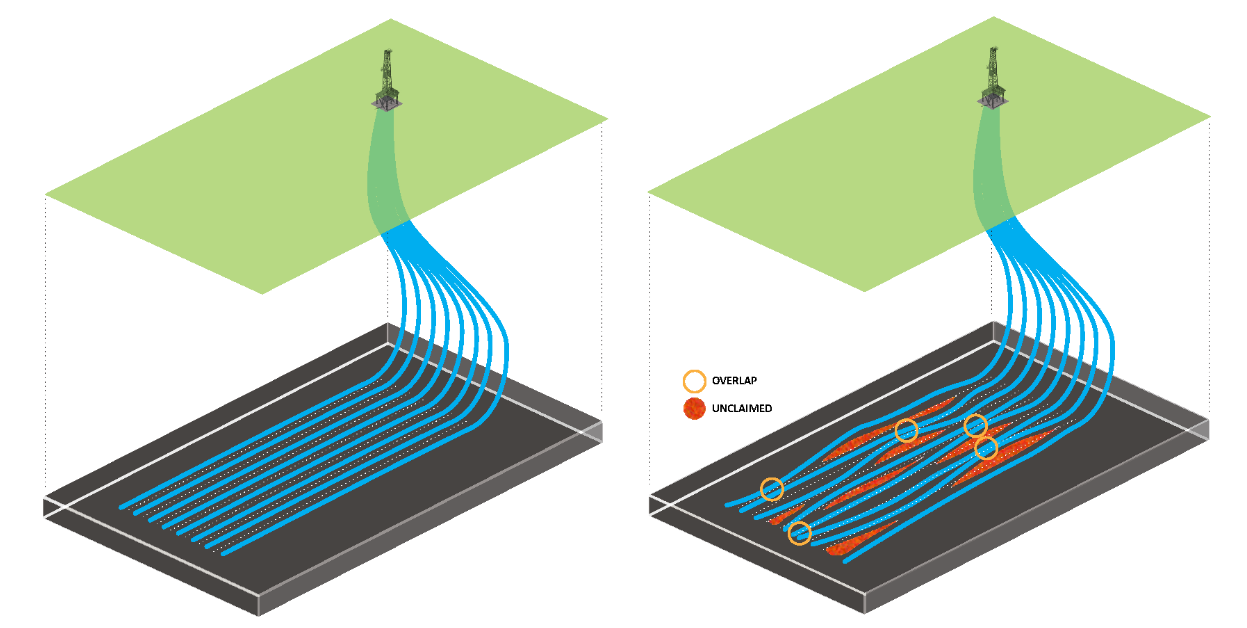

Figure 2: Planned (left) versus actual (right) wellbore trajectories. Position errors result in unclaimed production and communication.

Well path simulation and drainage modeling

A method was developed for simulating reservoir recovery that accounts for inaccuracies in well spacing due to wellbore positional uncertainty. This section first discusses the error sources represented by the commonly used surveying tool codes. This is followed by a description of how the well paths are simulated from these error models. Actual recovery losses are then computed assuming that drainage decays exponentially with horizontal distance from the wellbore. After providing further details about the publicly available simulator, some limitations of the method are discussed.

Error models

There are numerous error sources associated with MWD survey measurements and each error source contributes in some form to the magnitude of uncertainty that propagates along the computed wellbore trajectory. The Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA) developed a framework for quantifying the magnitude of uncertainty. The ISCWSA's work resulted in an error model which is described in detail by Williamson (2000). The Operators Wellbore Survey Group (OWSG), a sub-committee of the ISCWSA, continued development on the original error model and publishes a set of Instrument Performance Models that enable the computation of ellipses of uncertainty for specific surveying methods. This consolidated set is referred to as the OWSG set of tool codes.

There are two primary surveying choices affecting survey accuracy: The quality of the chosen geomagnetic reference model and the level of corrections applied to the survey data. Table 1 lists the sources of the geomagnetic field in the left column and shows how they are represented in the available reference models, increasing in accuracy from the left to the right column. Table 2 provides a corresponding list of the available survey corrections which are accounted for in the OWSG error models, again improving in accuracy from left to the right. These differences in survey accuracy are illustrated in Figure 1, which shows the difference between ellipses of uncertainty (EOU) for standard MWD versus advanced corrections using MWD+IFR2+MS+SAG.

Table 1: Differences between the chosen reference models, with accuracy improving to the right

	IGRF/ WMM	BGGM	MVHD	IFR1	IFR2
Main Field	✓	✓	✓	✓	✓
Annual update		✓	✓	✓	✓
Global crustal field			✓	✓	✓
Local crustal field				✓	✓
Local disturbance field					✓

Table 2: Available survey corrections represented in the OWSG tool codes

Some example tool codes	MWD +IFR1+AX	MWD +IFR1+MS	MWD +IFR2+SAG+MS
Axial interference	✓	✓	✓
Cross-axial interference, instrument biases and scale factors		✓	✓
BHA Sag			✓

Synthesis of wellbore trajectories

Figure 3 shows the well plan for a sample project with 10 wells drilled at 250 ft spacing within a 2500 ft. by 9000 ft. development area. The recovery simulator generates realistic wellbore trajectories using randomization at each survey station based on the error statistics specified by the tool codes. For every wellbore, a single systematic azimuth error value is generated using a random number generator scaled to the applicable tool error model. This systematic error is illustrated as the dashed blue line in Figure 4. The systematic error is applied equally at each survey station. In addition, a random error is generated for each well at each survey station, scaled to the random azimuth error of the tool code. This random error is illustrated in red in Figure 4. By applying these errors at every survey station, 10 meandering wellbore trajectories are generated, as illustrated in Figure 5. These wellbore trajectories can now be analyzed in terms of crossovers, lease line crossings and oil recovery. Repeating the simulation a large number of times enables a statistical assessment of the impacts of wellbore placement accuracy.

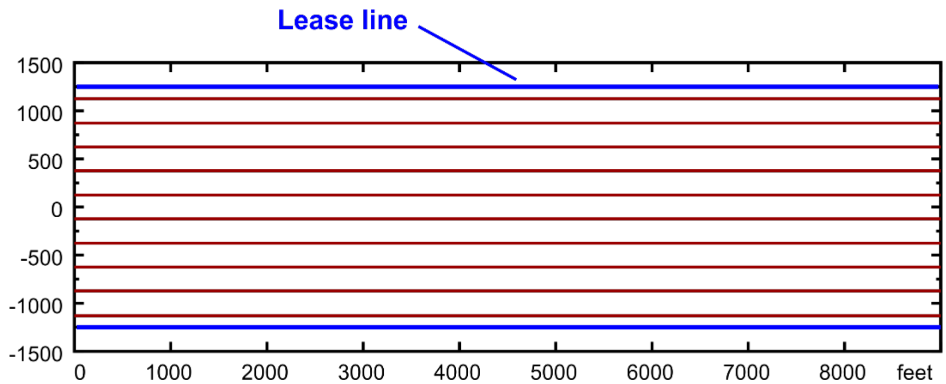

Figure 3: Planned well paths of a section with 10 wells

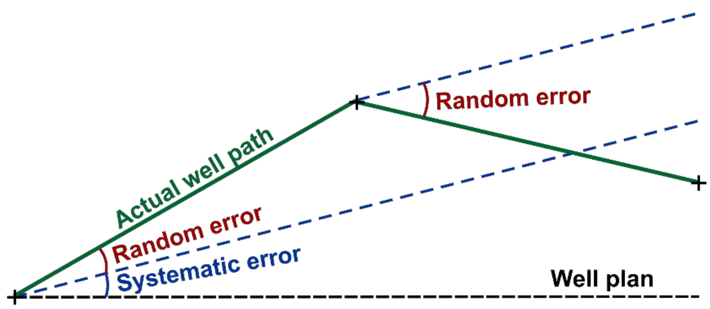

Figure 4: Well path simulation of systematic and random errors

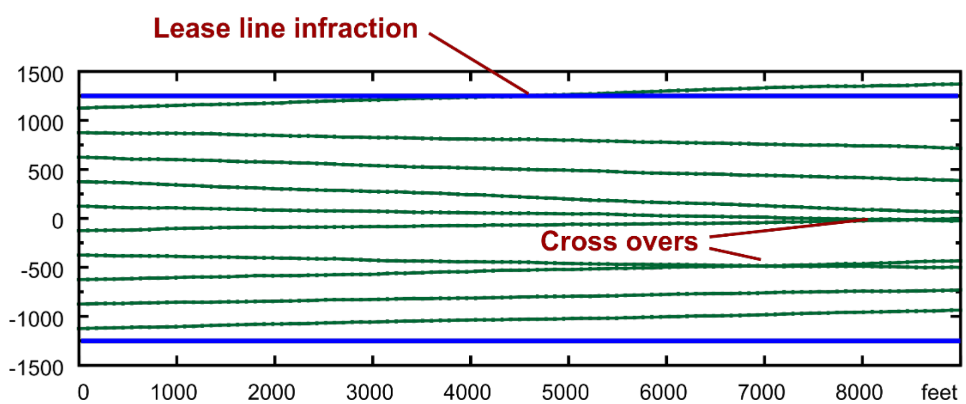

Figure 5: Simulated actual well paths for a section with 10 wells

Drainage envelope

In the case of horizontal wells drilled in shale formations, hydraulic fracturing is commonly used to break the rock and enable hydrocarbon flow into the wellbore. The fractures propagate radially from the wellbore at a limited distance into the rock. The fractured rock surrounding the wellbore creates a production envelope for which the wellbore can produce hydrocarbon fluids or gas. In other cases, the rock may already be sufficiently permeable for adequate recovery. In this case, the lateral propagation distance in the porous rock defines the production envelope.

Actual production does not occur from a fixed volume around the wellbore. Here, we assume that most of the production occurs within a formation-specific drainage radius, with exponential fall-off with distance. This assumption is well represented by a Gaussian bell shaped curve with the inflection points defined by as single parameter, which we call the drainage radius. This production envelope is illustrated in Figure 6 for a single wellbore. In the presence of multiple wellbores, the production envelopes overlap. In the overlap, it is assumed that total recovery from multiple wellbores is identical to the maximum value of the production envelopes of any of the wellbores. This is illustrated in Figure 7 for a well plan with 3 wellbores. Considering wellbore positioning errors then leads to the actual production envelopes shown in Figure 8. The difference between planned and actual recovery is then shown in Figure 9. The areas shaded in red correspond to lost production, while the areas shaded green correspond to increased production. It is seen that irregular wellbore placement increases the red areas, resulting in a small but significant loss of production.

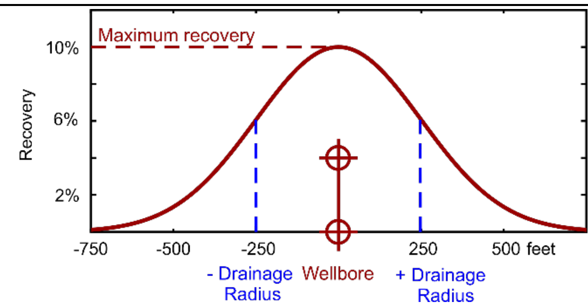

Figure 6: Assumed recovery as a function of lateral distance from the well bore

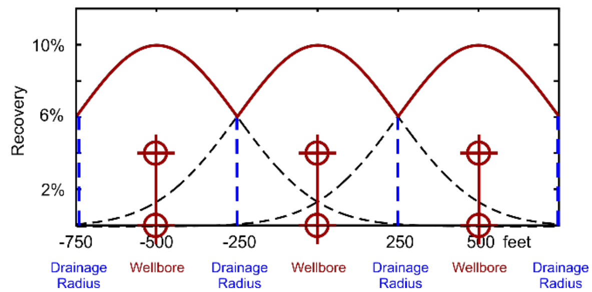

Figure 7: Ideal recovery from multiple wells with overlapping drainage envolopes

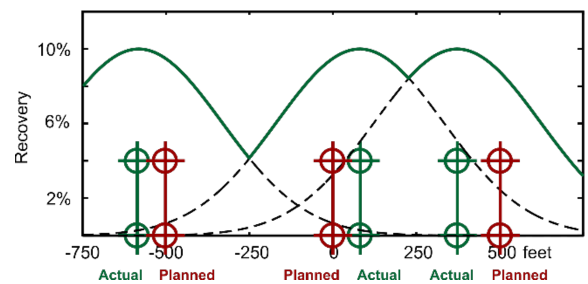

Figure 8: Actual recovery from multiple wells taking positioning errors into account

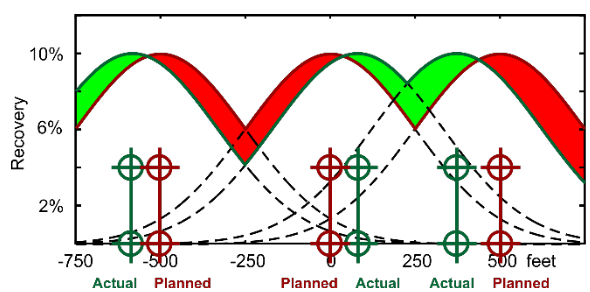

Figure 9: Difference between planned and actual recovery. Since losses (red) exceed gains (green), the result is a net loss of recovery

Web application

The simulator is available to the public under https://tools.magvar.com/mvrs as a web application (Figure 10). An economic analysis of different drilling scenarios may be performed with this web application to determine cost to benefit ratios for using enhanced surveying technologies by setting a price per volume of oil or natural gas and applying a cost to a particular tool code.

To run a simulation, the user enters the relevant reservoir parameters and chooses the OWSG tool codes of interest. The web application then simulates a large number of wells following the statistics of the OWSG error tool codes and computes the expected oil left in the ground due to inaccurate wellbore placement. The simulation assumes that the well spacing was chosen by the reservoir engineers to optimally drain the reservoir. The following parameters can be adjusted:

1. Which tool codes to include in the comparative simulation
2. Azimuth of the wellbores
3. Wellbore spacing
4. The number of parallel wells
5. Distance from the outer wellbores to the lease lines
6. The standard error of the wells' landing point uncertainty
7. Wellbore lateral length
8. Distance between subsequent surveys along the well path
9. Drainage radius
10. Ideal recovery as daily, annual or total number of barrels produced from the entire slab or from each well

The result is presented as summary statistics of the mean recovery, the mean loss and the maximum loss for each tool code. Since the simulation is based on an accurate implementation of the error tool codes, it can be used to investigate the effects of using tools of varying accuracy and adjusting the azimuth of the wellbore orientation. The simulator also reports any incidents in which wells accidentally crossed over each other or exited the permit area.

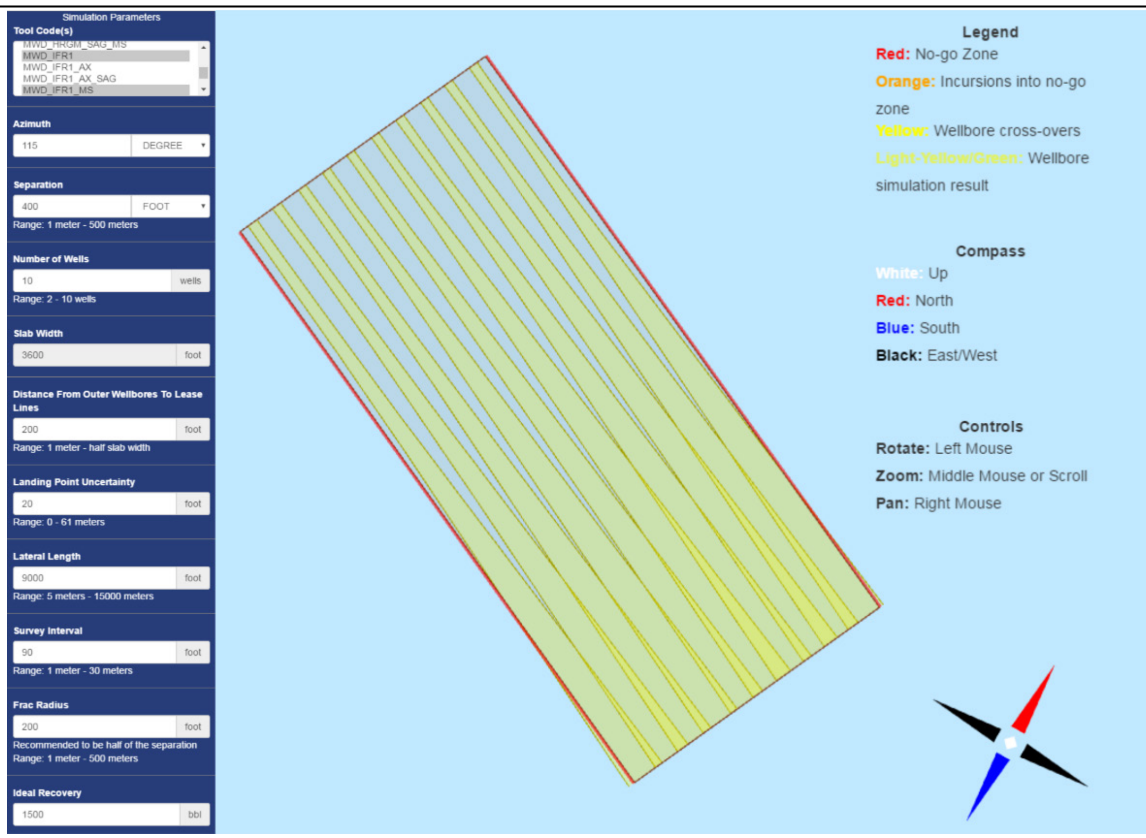

Figure 10: Screen shot of the MVRS reservoir simulator web application, available at https://tools.magvar.com/mvrs

Results

Simulations were carried out in active North American hydrocarbon regions for typical wellbore spacing and azimuths. Comparisons are made for the most commonly used tool codes, standard MWD versus In-Field Referencing and Multi-Station analysis (MWD+IFR+MS).

Wellbore cross-overs and lease line infractions

Table 3 summarizes the simulation results for western Alberta, the Bakken, Permian Basin and Eagle Ford. Positional errors generally increase with wellbore length, geographic latitude and with azimuths closer to magnetic east/west. These positional errors then manifest more severely the tighter the spacing. The results in Table 3 for MWD (red) reflect the combination of these different effects. The more accurate MWD+IFR+MS surveying method (green) cuts the positional errors roughly in half, which almost eliminates any cross-overs and lease line infractions. Here, the lease lines were assumed to be at a distance of half the spacing from the outer wellbores, such as 200 ft in Eagle Ford, for example. Drilling closer would significantly increase the danger of crossing a lease line.

Table 3: Cross-overs and lease line infringements for typical wellbore geometries in some active basins of North America

Well Plans				MWD		MWD+IFR+MS	
Region	**Lateral length**	**Azimuth**	**Spacing**	**Lease crossings**	**Wellbore crossovers**	**Lease crossings**	**Wellbore crossovers**
Alberta West	2500 m	315°	120 m	14.5%	7.1%	0.1%	0.0%
Bakken E/W	9600 ft	90°	500 ft	9.2%	3.6%	0.0%	0.0%
Permian	9200 ft	165°	330 ft	4.8%	0.8%	0.0%	0.0%
Eagle Ford	8000 ft	145°	400 ft	0.8%	0.2%	0.0%	0.0%

Recovery simulations

To simulate recovery for the same hydrocarbon regions, it was assumed that the drainage radius was half the wellbore spacing. Simulations were again run for MWD versus MWD+IFR+MS to estimate the recovery losses for wellbores steered by either of these surveying methods. The smaller losses of wellbore placement using the more accurate MWD+IFR+MS can then be translated into a net recovery increase, which is shown in the 5th column of Table 4. To convert recovery percentages into barrels of oil (column 6), a typical daily production of 1500 bbl/day was used. Scaled to one year and converted using $50/bbl gives the annual gain per well of using more accurate surveying techniques in the right hand column of the table.

Table 4: Simulated production increase resulting from using a more accurate surveying method (MWD+IFR+MS) instead of standard MWD.

Region	Lateral length	Azimuth	Spacing	Recovery increase	Production/day	bbl/year	@$50/bbl
Alberta West	2500 m	315°	120 m	+ 1.8%	+27 bbl	+ 9855 bbl	+ $492,750
Bakken E/W	9600 ft	90°	500 ft	+ 1.9%	+28 bbl	+ 10,400 bbl	+ $520,000
Permian	9200 ft	165°	330 ft	+ 0.8%	+12 bbl	+ 4380 bbl	+ $219,000
Eagle Ford	8000 ft	145°	400 ft	+ 0.7%	+10.5 bbl	+ 3833 bbl	+ $191,650

Effect of wellbore lateral length on crossings and recovery losses

Developments using long-reach wells face additional challenges due to accumulating positional errors. The recovery simulator can be used to investigate the effect of wellbore length on recovery losses. A typical scenario for Eagle Ford is shown in Table 5, comparing wellbore cross-overs and lease line infractions between 8000 ft and 11,000 ft wells. As seen, the likelihood of incidents increases drastically with longer wellbores when using standard MWD. The more accurate MWD+IFR+MS surveying method effectively prevents such incidents. Of course, for tighter spacing or even longer wells, one can expect to see an increased incidence rate even for the more accurate surveying method.

Table 5: Effect of wellbore lateral length on crossovers

				MWD		MWD+IFR+MS	
Region	**Lateral length**	**Azimuth**	**Spacing**	**Lease crossings**	**Wellbore crossovers**	**Lease crossings**	**Wellbore crossovers**
Eagle Ford	8000 ft	145°	400 ft	0.8%	0.2%	0.0%	0.0%
Eagle Ford	11,000 ft	145°	400 ft	6.7%	1.8%	0.0%	0.0%

The lateral length also has an impact on production losses. Due to the larger losses at longer wellbore lengths, the benefit of using more accurate surveying methods increases with wellbore length accordingly. This is shown in Table 6, again comparing the 8000 ft versus 11,000 ft wells in Eagle Ford. Assuming a linear production increase of 37.5% with length from 1500 bbl/day to 2062 bbl/day, it is seen that the benefit of using the more accurate surveying method increases disproportionately by 116% from $191,650 to $414,250 per year.

Table 6: Effect of wellbore lateral length on production increases achieved by using MWD+IFR+MS steering instead of standard MWD

Region	Lateral length	Daily production	Recovery increase	Prod/day	bbl/year	@$50/bbl
Eagle Ford	8000 ft	1500 bbl/well	+ 0.7%	+10.5 bbl	+ 3833 bbl	+ $191,650
Eagle Ford	11,000 ft	2062 bbl/well	+ 1.1%	+22.7 bbl	+ 8285 bbl	+ $414,250

Effect of wellbore lateral length on crossings and recovery losses

Similar comparisons can be carried out for the influence of the orientation of the wellbores. It is well known that horizontal wellbores drilled east/west have significantly larger positional errors than wellbores drilled north/south. This effect is simulated here on example wells in the Bakken. Table 7 shows a significantly higher likelihood of cross-over incidents for east/west oriented wells when using standard MWD (red values). The improved placement when steering with MWD+IFR+MS alleviates this problem (green values).

Table 7: Effect of wellbore azimuth on crossings

				MWD		MWD+IFR+MS	
Region	**Lateral length**	**Azimuth**	**Spacing**	**Lease crossings**	**Wellbore crossovers**	**Lease crossings**	**Wellbore crossovers**
Bakken E/W	9600 ft	90°	500 ft	9.2%	3.6%	0.0%	0.0%
Bakken N/S	9600 ft	180°	500 ft	0.9%	1.0%	0.0%	0.0%

Due to the higher recovery losses on east/west oriented wells, the simulation shows a correspondingly larger production benefit for MWD+IFR+MS steering. While MWD+IFR+MS is already widely used to mitigate small separation factors on east/west oriented wells, the recovery simulation results in Table 8 show that there is an additional economic rationale for paying particular attention to survey accuracy on those wells.

Table 8: Effect of wellbore azimuth on production: East/West versus North/South oriented wells

Region	Lateral length	Azimuth	Spacing	Recovery increase	Prod/day	bbl/year	@$50/bbl
Bakken E/W	9600 ft	90°	500 ft	+ 1.9%	+28 bbl	+ 10,400 bbl	+ $520,000
Bakken N/S	9600 ft	180°	500 ft	+ 0.8%	+12 bbl	+ 4380 bbl	+ $219,000

Limitations and discussion

This simulation tool is not designed for optimizing lateral well spacing or determining the optimal number of wells to place in a production field. The underlying assumption is that the drainage radius is already known, so the user should choose input parameters for lateral spacing and number of wells based on existing knowledge. However, it should be recognized that if wellbore positional uncertainty was not considered when initial spacing tests were conducted, assumptions about the drainage radius may not be accurate. In general, this simulation provides a conservative estimate of the impact of wellbore positioning errors. Actual recovery losses may be significantly larger than simulated, for the following reasons:

1) The simulation optimistically assumes that surveying requirements are being fully followed such as:
   a) Surveys are quality controlled
   b) MWD tools are calibrated to meet the specifications of the tool code
   c) Survey intervals are sufficient to represent the wellbore trajectory
2) The simulation does not account for gross errors, such as applying incorrect declination or grid convergence.
3) Only lateral placement errors are considered. In reality, vertical depth errors can contribute significantly to production losses.
4) The ISCWSA error models assume Gaussian error distributions, while actual survey errors are known to have heavy tailed distributions. Consequently, large wellbore position errors are more likely than indicated by the error models.

Conclusions

Enhanced surveying practices have historically been driven by the need to reduce positional uncertainty in order to satisfy anti-collision requirements. There was little concern where the wellbore actually ended up as long as it did not collide with another wellbore. However, now that shale plays are being developed with closely spaced long reach horizontal wellbores, it is becoming increasingly important to achieve accurate wellbore placement. Shale economics are highly dependent on the ability to drain a field as efficiently as possible. Until now, there has been little progress quantifying the impact of survey accuracy on reservoir drainage. While the simulations presented in this paper have limitations and uncertainties, they provide estimates that clearly show a significant economic case for improving survey accuracy. Not only does accurate wellbore placement provide a direct increase in wellbore value through optimized reservoir drainage, but there are also numerous other indirect benefits including improved reservoir modeling, better interpretation of spacing tests, reduction in wellbore cross overs, and decreased risk of lease line infractions.

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